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Single spin asymmetry in inclusive pion production, Collins effect and the string model

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Abstract

We calculate the single spin asymmetry in the inclusive pion production in proton-proton collisions. We generate the asymmetry at the level of fragmentation function (Collins effect) by the Lund coloured string mechanism. We compare our results with the Fermilab E704 data from $p\uparrow p$ collisions at 200 GeV. We show that the transversely polarized quark densities at high Bjorken x strongly differ from these predicted by the SU(6) proton wave function.

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1. Introduction

Quantum Chromodynamics predicts that single transverse spin asymmetries are suppressed in hard collisions, as a consequence of helicity conservation (chiral invariance) in the subprocess. These asymmetries indeed appear as interferences between helicity amplitudes which differ by one unit of helicity, therefore they vanish in the limit $m_{\rm quark} \to 0$, or equivalently $Q^2 \to \infty$ (Q measures the hardness of the subprocess). Nevertheless, a number of high p_T reactions persist in showing large asymmetries [1].

These facts do not invalidate QCD but mean that the approach to the asymptotic regime in $p_\perp$ is very slow, as regards polarization. However, in spite of their "nonasymptotic" character, it is not unreasonable to think that the mechanisms of the asymmetries lie at the parton level. In other words, the asymmetries would be manifestations of quark transverse spin (or *transversity*). Thus, we could extract information from them about the quark transversity distribution in the nucleon and/or the transversely polarized quark fragmentation. In this paper, we shall present a model for the spin asymmetry in the reaction

$$p\uparrow + p \to \pi + X \tag{1.1}$$

which, unlike previous approaches [2,3], involves the transverse spin asymmetry of the polarized quark fragmentation [4,5], which hereafter will be refered to as the Collins effect.

The paper is organized as follows: section 2 gives a very short review of the results of Fermilab E-704 experiment. In section 3, we explain how the Collins asymmetry can give rise to the observed single spin asymmetry in reaction (1.1) and deduce lower bounds on the transverse polarizations of the quarks in the proton, as well as on the size of the Collins effect. Section 4 presents a quantitative model based on string fragmentation and section 5 gives the numerical results. Section 6 contains discussion of our results and conclusions.

2. Main features of single spin asymmetry in inclusive pion production

A strong polarization effect has been observed in the reaction (1.1) with 200 GeV transversely polarized projectile protons. The asymmetry is defined as

$$A_N(x_F, p_\perp) \equiv \frac{\sigma\uparrow - \sigma\downarrow}{\sigma\uparrow + \sigma\downarrow}, \tag{2.1}$$

Assuming that $\uparrow$ refers to the $+\hat{y}$ direction (vertical upwards), and the transverse momentum $\vec{p}_\perp$ of the pion points towards the $+\hat{x}$ direction ($\vec{p}_{\rm beam}$ is along the $\hat{z}$ axis). In other words positive A_N means that for upward polarization, the pions tend to go to the left. The most recent results, which we will consider in this paper, come from the Fermilab E-704 collaboration. They were published separately for two kinematical regions:

- $x_F > 0$ or fragmentation region. The asymmetries have been measured for both charged and neutral pions [6–8].
- Central region, $x_F \sim 0$ [9], where the asymmetries were measured for neutral pions only. Large asymmetries for high $p_\perp$ in the central region had been observed previously also by other experimental groups [10]

(x_F is the Feynman variable $2p_z^{\rm CM}/\sqrt{s}$ with $p_z^{\rm CM}$ being the longitudinal momentum of the pion in the CM frame).

In this paper we shall concentrate only on the first case. In this region the data show large asymmetry for all pions; positive for π^+ and π^0 and negative for π^-. The asymmetries vary from about 0 at $x_F \sim 0.2$ to about $+0.4$, $+0.15$ and -0.4, for π^+, π^- and π^- respectively, at $x_F \sim 0.7 - 0.8$.

3. Hypothesis that E-704 asymmetry is due to Collins effect

3.1 Generalities from the parton model.

In the "factorized" parton model (Fig. 1), the cross section for $A+B \to \pi+X$ in the forward hemisphere is a kind of convolution of a parton distribution $G_{q/A}(x, \vec{q}_\perp)$, a parton scattering cross section $\hat{\sigma}_{q+B\to q'+X} \equiv \hat{\sigma}_{q\to q'}$ and a parton fragmentation function $D_{\pi/q'}(z, \vec{h}_\perp)$. In short-hand notations,

$$\sigma_{A\to\pi} \approx G_{q/A} \otimes \hat{\sigma}_{q\to q'} \otimes D_{\pi/q'} \tag{3.1}$$

[the factor $\hat{\sigma}_{q\to q'}$ may be replaced by $\delta(\vec{q} - \vec{q}\,')$ (no scattering); this is the case of the Dual Parton Model]. Each factor in this equation may or may not depend on spin. Transverse polarization can act at three different levels:

a) in a dependence of $G_{q/A}(x, \vec{q}_\perp)$ on the azimuth of $\vec{q}_\perp$ (Sivers effect [2]).
b) in a single spin asymmetry in $\hat{\sigma}_{q\to q'}$ (Szwed effect [3]). In this case, (but not necessarily in case *a*), the quark q must inherit a part of the polarization of the proton.
c) in a dependence of $D_{\pi/q'}(z, \vec{h}_\perp)$ on the azimuth of $\vec{h}_\perp$ (Collins effect [4,5]). Here, a transfer of polarization must occur not only from the proton to quark q but also from q to q'.

The first mechanism implies nonzero internal angular momentum inside the proton, hence a strong departure from SU(6) model. As for mechanisms *b*) and *c*), SU(6) predicts :

$$A_N^{\pi^-} \simeq -\frac{1}{2}\, A_N^{\pi^+} \qquad \text{and} \qquad \left| A_N^{\pi^-} \right| \leq \frac{1}{3}, \tag{3.2}$$

since most of the time, π^+ comes from a valence u-quark, π^- from a valence d-quark of the projectile and the polarizations of u and d are respectively $+\frac{2}{3}$ and $-\frac{1}{3}$. These predictions are in conflict with the E-704 results $A_N^{\pi^+} \simeq -A_N^{\pi^-} \simeq 0.4$ at large x_F. To conclude, whichever mechanism we choose, SU(6) appears to be badly violated in $G_{q/p}(x, q_\perp)$.

3.2 The Collins effect.

According to Collins [4,5], the fragmentation function of a transversely polarized quark q takes the form

$$D_{\pi/q}(\vec{\mathcal{P}}_q, z, h_\perp) = \bar{D}_{\pi/q}(z, h_\perp) \left\{ 1 + \mathcal{A}_{\pi/q}(z, h_\perp) \times |\vec{\mathcal{P}}_q| \times \sin[\varphi(\vec{\mathcal{P}}_q) - \varphi(\vec{h}_\perp)] \right\} , \tag{3.3}$$

where $\vec{\mathcal{P}}_q$ is the quark polarization vector ($|\vec{\mathcal{P}}_q| \leq 1$), $\vec{h}_\perp$ the pion transverse momentum relative to the quark momentum $\vec{q}$ and $\varphi(\vec{a})$ the azimuth of any vector $\vec{a}$ about $\vec{q}$. The factors after $\mathcal{A}$ can be replaced by $|\vec{q} \times \vec{h}_\perp|^{-1}\, \vec{\mathcal{P}}_q \cdot (\vec{q} \times \vec{h}_\perp)$. Such a dependence is allowed by P- and T- invariance but has not yet been measured.

The Collins effect is the reciprocal of the Sivers effect. But Collins argued that the later is prohibited by time reversal invariance [4], while the former is not. As for mechanism b), it vanishes for massless quarks due to chiral symmetry: single spin asymmetry in $q \to q'$ is not compatible with conservation of quark helicity. Therefore it should be small for hard or semi-hard scattering. In conclusion, among the sources of asymmetry a), b) and c) discussed above, we have a preference for the Collins effect illustrated by Fig. 1.**

3.3 Consequence for the single spin asymmetry.

Let us consider the hypothesis that E-704 asymmetry is due to the Collins effect. The polarized inclusive cross section reads

$$\frac{d\sigma}{d^3\vec{p}} = \sum_{\text{flavours of q, k, q}'} \int dx\, d^2\vec{q}_\perp\ G_q(x,\vec{q}_\perp) \int dy\, d^2\vec{k}_\perp\ G_k(y,\vec{k}_\perp) \times$$

$$\int d(\cos\hat{\theta})\, d\hat{\varphi}\, \frac{d\hat{\sigma}^{q+k\to q'+k'}}{d\hat{\Omega}} \int dz\, d^2\vec{h}_\perp\ D_{\pi/q'}(\vec{\mathcal{P}}_{q'}, z, \vec{h}_\perp)\, \delta(\vec{p} - z\vec{q}\,' - \vec{h}_\perp)\ ; \qquad (3.4)$$

the final quark transversity is given by

$$\vec{\mathcal{P}}_{q'} = \mathcal{R}\ \vec{\mathcal{P}}_{\rm beam}\ \frac{\Delta_\perp G_q(x,\vec{q}_\perp)}{G_q(x,\vec{q}_\perp)}\ \hat{D}_{NN}(\hat{\theta})\,. \qquad (3.5)$$

$\mathcal{R}$ is the rotation about $\vec{p}_{\rm beam} \times \vec{q}\,'$ which brings $\vec{p}_{\rm beam}$ along $\vec{q}\,'$,

$$\Delta_\perp G_q(x,\vec{q}_\perp) \equiv G_{q\Uparrow}(x,\vec{q}_\perp) - G_{q\Downarrow}(x,\vec{q}_\perp) \qquad (3.6)$$

is the quark *transversity distribution* [12,13] in the proton polarized upwards, and $\hat{D}_{NN}(\hat{\theta})$ is the coefficient of spin transfer normal to the scattering plane in the subprocess. Formula (3.1) results from integration over the target parton variables y and $\vec{k}_\perp$.

At large x_F, the dominant quark flavours are $q = q' = u$ for π^+ production, $q = q' = d$ for π^- production. Furthermore, the hard scattering occurs predominantly at small $\hat{\theta}$ and $\hat{D}_{NN}(\hat{\theta})$ is close to unity, as in the case of $\hat{t}$-channel one-gluon exchange $[\,\hat{D}_{NN} = -2\hat{s}\hat{u}/(\hat{s}^2+\hat{u}^2)\,]$. Assuming that $\Delta_\perp G_q/G_q$ does not depend on $\vec{q}_\perp$, the results of E704 collaboration imply

$$\frac{\Delta_\perp G_u(\bar{x})}{G_u(\bar{x})} \times \mathcal{A}(\bar{z}, \bar{h}_\perp) \geq \text{about } 0.4\,, \qquad (3.7)$$

$$\frac{\Delta_\perp G_d(\bar{x})}{G_d(\bar{x})} \times \mathcal{A}(\bar{z}, \bar{h}_\perp) \leq \text{about } -0.4\,, \qquad (3.8)$$

** We shall not discuss other approaches [11] not relying on the factorized parton description (Eqs. 3.1 or 3.4). They are not necessarily in contradiction with the present one.

for $\bar{x}\bar{z} \simeq x_F \simeq 0.8$. $\bar{x}$ means the most probable value of x. The inequalities take into account the fact that integration over $\vec{q}_\perp$ and $\hat{\theta}$ allways dilutes the Collins effect. Thus, we get at least a lower bound of 0.4 separately for $|\Delta_\perp G_u/G_u|$, $|\Delta_\perp G_d/G_d|$ at large x and $|\mathcal{A}(z,h_\perp)|$ at large z and for the most probable value of $h_\perp$.

4. Simple model of single spin asymmetry

In order to make the conclusions of the previous section more quantitative, we performed a calculation in a simple model.

We considered only the valence quarks of the projectile proton with distributions normalized as follows:

$$\sum_{q=u,d} \int d^2\vec{q}_\perp \int dx \; G_q(x,\vec{q}_\perp) = 1 \, ; \qquad G_u = 2\, G_d \, . \tag{4.1}$$

$[G_q(x) = \frac{1}{3} q_{val}(x)$ in conventional notations]. The quark is accompanied by a diquark carrying the fractional momentum $1-x$ and whose distribution is

$$G_{uu}(x,\vec{q}_\perp) = G_d(1-x,-\vec{q}_\perp) \, ; \quad G_{ud}(x,\vec{q}_\perp) = G_u(1-x,-\vec{q}_\perp) \, . \tag{4.2}$$

We did not incorporate any hard or semihard scattering. Both $\mathcal{R}$ and $\hat{D}_{NN}$ of Eq. (3.5) are equal 1. The two $q - qq$ strings formed after the collision are parallel to the beam. We decay them recursively according to the simple Lund recipe [14]. We use the Standard Lund splitting function:

$$f(z) = (1+C)(1-z)^C \, , \tag{4.3}$$

z being the fraction of the null plane momentum $P^+ \equiv P^0 + P^3$ of the string carried by its leading hadron. $f(z) = D^{\mathrm{rank}=1}(z)$ corresponds to the production rate of the first-rank hadron (*i.e.* the one that contains the original quark spanning the string). This gives [14] for all ranks the inclusive density:

$$D^{\mathrm{all\ ranks}}(z) = (1+C)\frac{1}{z}(1-z)^C = \frac{1}{z} f(z). \tag{4.4}$$

Thus, for all the other (subleading) hadrons originating from the string we get:

$$D^{\mathrm{rank}\geq 2}(z) = (1+C)\frac{1-z}{z}(1-z)^C = f(z)\frac{1-z}{z}. \tag{4.5}$$

The transverse momenta of a quark and an antiquark of a pair created in the string balance each other (local compensation of the transverse momentum) and are distributed according to

$$\rho(\vec{q}_\perp)\, d^2\vec{q}_\perp = \frac{d^2\vec{q}_\perp}{\kappa} \exp\left(\frac{-\pi q_\perp^2}{\kappa}\right) , \tag{4.6}$$

κ being the string tension. We took the intrinsic transverse momentum distribution in $G_q(x,\vec{q}_\perp)$ to be the same as for the tunnelling transverse momentum in the string:

$G_q(x, \vec{q}_\perp) = G_q(x)\ \rho(\vec{q}_\perp)$. It yields an average intrinsic transverse momentum $\langle q_\perp^{\rm intrinsic}\rangle = 0.206\,{\rm GeV}$.

The polarization of the leading quark q_0 is

$$\vec{\mathcal{P}}_{q_0}(x) = \frac{\Delta_\perp G_{q_0}(x, \vec{q_0}_\perp)}{G_{q_0}(x, \vec{q_0}_\perp)} \cdot \hat{y} \tag{4.7}$$

and is taken to depend only on x.

Each quark-antiquark pair created during string breaking is assumed to be in a $^3P_0$ state (vacuum quantum numbers) [15], *i.e.,* with parallel polarizations. According to the Lund mechanism for inclusive Λ polarization [14], their polarizations are correlated to the transverse momentum of the antiquark $\vec{\bar{q}}_\perp$ by

$$\vec{\mathcal{P}}_q = \vec{\mathcal{P}}_{\bar{q}} = -\,\frac{L}{1+L} \cdot \frac{\hat{z} \times \vec{\bar{q}}_\perp}{\bar{q}_\perp}\,, \tag{4.8}$$

where L is the classical orbital angular momentum of the $q\bar{q}$ pair and equals:

$$L = \frac{2\ \bar{q}_\perp \sqrt{m_q^2 + \bar{q}_\perp^2}}{\kappa} \simeq \frac{2\ \bar{q}_\perp^2}{\kappa}, \tag{4.9}$$

(see Fig. 2 for a schematic explanation).

In order that q_0 and $\bar{q}_1$ of Fig. 2 combine into a pion, they have to form a spin singlet state, the probability of which is

$$\frac{1}{4}\,(1 - \vec{\mathcal{P}}_{q_0} \cdot \vec{\mathcal{P}}_{\bar{q}_1})\,, \tag{4.10}$$

in accordance with the projector on the singlet state $\frac{1}{4} - \vec{s}(q_0)\cdot\vec{s}(\bar{q}_1)$. The factor (4.10) causes the Collins effect: if q_0 in Fig. 2 is polarized upwards then $\bar{q}_1$ and the pion which contains $\bar{q}_1$ tends to go to the left-hand-side of the $\hat{z}$ direction.

Vector mesons are ignored (accordingly, we omit the factor $\frac{1}{4}$ in Eq. (4.10)). In our model the asymmetry for vector mesons would be of the opposite sign but three times smaller in magnitude when compared to that of the scalar ones. The observed asymmetry of the pions resulting from decays of the vector mesons would be even smaller, due to integration over decay angles[†]. Anyway, at large x_F, there are mostly direct pions.

We do not introduce the Collins effect in subleading ranks or in the fragmentation of the diquark. For the fragmentation function (4.3), the probability that the detected pion is the leading one is equal to its momentum fraction z. Hence, the model can be a good approximation mostly for pions of high positive x_F. We provide a short discussion of this

[†] It has been shown however that the vector meson can also have a *tensor* polarization [16] which would result in the Collins effect for the decay products. We did not include this possibility. Another source of asymmetry [5] could be the interference between the vector meson and the nonresonating background.

point in the last section. We shall divide the sources of the pion production into three parts:

1. the pion is the leading particle of the string spanned by the quark q_0. The Collins effect (and the asymmetry) appears only in this contribution.
2. The pion is a subleading particle of the string spanned by that quark, or
3. it is a subleading particle of the string spanned by the diquark accompanying the quark q_0. The leading particle of the string in this case is a baryon. Taking into account that $x_F \approx xz$ and that the transverse momentum of the pion is the sum of the transverse momenta of its constituents we get the production rates for all the three cases:

$$\frac{1}{\sigma_{\rm tot}}\left[\frac{d\sigma}{dx_F d^2\vec{p}_\perp}\right]^{\rm rank=1}_{\rm quark} = \sum_{q=u,d}\int dx\, dz\, d^2\vec{q}_\perp\, d^2\vec{\bar{q}}_\perp G_q(x,\vec{q}_\perp)\; c_1\; D^{\rm rank=1}(z)$$
$$\times\left(1-\vec{\mathcal{P}}_q\cdot\vec{\mathcal{P}}_{\bar q}(\vec{\bar{q}}_\perp)\right)\;\rho(\vec{\bar{q}}_\perp)\;\delta(x_F-xz)\;\delta^2(\vec{p}_\perp-\vec{q}_\perp-\vec{\bar{q}}_\perp) \tag{4.11}$$

$$\frac{1}{\sigma_{\rm tot}}\left[\frac{d\sigma}{dx_F d^2\vec{p}_\perp}\right]^{\rm rank\,\geq\,2}_{\rm quark} = \sum_{q=u,d}\int dx\, dz\; G_q(x)\; c_2\; D^{\rm rank\,\geq\,2}(z)\;\rho_\pi(\vec{p}_\perp)\;\delta(x_F-xz) \tag{4.12}$$

$$\frac{1}{\sigma_{\rm tot}}\left[\frac{d\sigma}{dx_F d^2\vec{p}_\perp}\right]^{\rm rank\,\geq\,2}_{\rm diquark} = \sum_{q=u,d}\int dx\, dz\; G_{qq}(x)\; c_3\; D^{\rm rank\,\geq\,2}(z)\;\rho_\pi(\vec{p}_\perp)\;\delta(x_F-xz) \tag{4.13}$$

and the total production rate is the sum of the three:

$$\frac{d\sigma}{dx_F d^2\vec{p}_\perp} = \left[\frac{d\sigma}{dx_F d^2\vec{p}_\perp}\right]^{\rm rank=1}_{\rm quark} + \left[\frac{d\sigma}{dx_F d^2\vec{p}_\perp}\right]^{\rm rank\,\geq\,2}_{\rm quark} + \left[\frac{d\sigma}{dx_F d^2\vec{p}_\perp}\right]^{\rm rank\,\geq\,2}_{\rm diquark} \tag{4.14}$$

$\rho_\pi(\vec{p}_\perp)$ is the convolution of $\rho(\vec{q}_\perp)$ and $\rho(\vec{\bar{q}}_\perp)$ and is also Gaussian but of twice larger variance‡. c_1, c_2 and c_3 are flavour factors and correspond to the probability that q and $\bar{q}$ match to form a pion of the appropriate charge.

Since the production rate varies with the azimuthal angle of the pion momentum ϕ like in (3.3) then, in order to obtain the asymmetry at given values of $p_\perp$ and x_F, we need to compare $d\sigma(x_F, p_\perp, \phi)$ only at $\phi = 0$ and $\phi = \pi$:

$$A_N(x_F,p_\perp) = \frac{d\sigma(x_F,p_\perp,0)-d\sigma(x_F,p_\perp,\pi)}{d\sigma(x_F,p_\perp,0)+d\sigma(x_F,p_\perp,\pi)} \tag{4.15}$$

‡ We did not follow exactly the $\delta(\vec{p}-z\vec{q}\,'-\vec{h}_\perp)$ prescription of (3.4) ; in other words we gave all the transverse momentum of the leading quark to the first rank particle. The resulting error is small at large x_F.

which completes the calculation.

5. Numerical results

For the numerical calculations we parametrized the quark distributions as follows:

$$G_u(x) = 2\ G_d(x) = \frac{5}{2}\ x^{1/2}\ (1-x). \tag{5.1}$$

We have used the string tension $\kappa = 0.17$ GeV^2 and the parameter of the fragmentation function $C = 0.3$. In pair creation we have used the flavour abundances with the ratio $u : d : s = 3 : 3 : 1$, which determine the coefficients in Eqs (4.11–4.13) to be $c_1 = 3/7$, $c_2 = c_3 = 9/49$ for charged and $c_2 = c_3 = 18/49$ for neutral pions[§].

In Fig. 3a we show our results compared to the data [7] of $0.7 < p_\perp < 2.0$ GeV. The dotted, dashed and full lines correspond to various dependences of the quark polarization $\mathcal{P}_q$ on the momentum fraction x: constant, proportional to x and to x^2 respectively. Results obtained for all the three choices converge at $x_F = 1$. The maximal values of the polarization, reached at $x = 1$, are those motivated by the SU(6) wave function of the proton: $\mathcal{P}_u = +2/3$ and $\mathcal{P}_d = -1/3$.

One sees that the resulting asymmetry A_N strongly disagrees with the data for the negative pions. This confirms the conclusion of the Section 2. The measured asymmetries in π^- production are, for $x_F >\sim 0.5$, equal in the absolute value but of the opposite sign to those of π^+. This cannot be accounted for by SU(6) where the asymmetry of π^- is negative but twice smaller than that of π^+.

The results compared to the data at lower transverse momenta, $0.2 < p_\perp < 0.7$ GeV, are shown in Fig. 3b. Here no disagreement with the data is seen. The data do not reach however as high values of x_F as in the high $p_\perp$ interval.

The behaviour of the measured asymmetries at high x_F and $p_\perp$ encouraged us to try out a parametrization with maximal possible transverse polarizations of quarks one could choose in the proton: $\mathcal{P}_u = 1$ and $\mathcal{P}_d = -1$ at $x = 1$. The results are plotted in Figs. 4a and 4b for both $p_\perp$ intervals. The constant polarizations $\mathcal{P}_q(x) =$ const (dotted lines) result in too large asymmetry, at least at small and intermediate x_F. This suggests that the transversely polarized quark densities fall down at small Bjorken x values.

The full lines follow the data quite well. Only the measured asymmetries of π^- slightly differ from our results at small values of both x_F and $p_\perp$. One might conclude that $\Delta_\perp G_q(x)/G_q(x)$ varies with x somwhere around x^2 but such conclusion is dangerous in scope of the simplicity of the model.

In order to check how our results depend on the shape of the quark distribution $G_q(x)$ we did the calculation also for

$$G_q(x) \sim x^{-1/2}, \tag{5.2}$$

[§] In this model, every $u\bar{u}$ or $d\bar{d}$ meson is considered as a π^0 (no η^0) ; it gives $\sigma(\pi^+) + \sigma(\pi^-) = \sigma(\pi^0)$, instead of $2\ \sigma(\pi^0)$ as required by isospin. Nevertheless, Eq. (5.3) below remains true.

which differs strongly from (5.1) but gives better account of the leading baryonic effect ($G_{qq}(x) \sim (1-x)^{-1/2}$ and the diquark tends to carry a substantial momentum fraction of the proton). The comparison is shown in Fig. 5. One sees that for the distribution (5.2) the asymmetry (dashed line) is slightly smaller at large x_F but the difference is not large. The full line comes from Fig. 4 and corresponds to the distribution (5.1).

In the parton model the π^0 asymmetry is just a combination of the π^+ and π^- ones :

$$A_N(\pi^0) = \frac{\sigma(\pi^+)\ A_N(\pi^+) + \sigma(\pi^-)\ A_N(\pi^-)}{\sigma(\pi^+) + \sigma(\pi^-)}\,. \tag{5.3}$$

Nevertheless, we show in Fig. 6 a comparison of our results to the E704 data [6] on π^0 production in pp and $\bar{p}p$ collisions. The curve obtained with $\mathcal{P}_q(x) \sim x^2$ (full line) agrees with the data also here. The lower $p_\perp$ bound in the π^0 case varies from 0.5 to 0.8 GeV depending on x_F and was taken into account in our calculation. This is the reason of a bit wiggly shape of the lines. For the neutral pions the difference between SU(6) and the maximal polarizations of the quarks in the proton cancels and there is no difference in our predictions there.

Finally, in Fig. 7 we plot the $p_\perp$ dependence of the asymmetry of π^0. The agreement with the data is also good. The shape of the curves reflects the Lund parametrization (4.8). Only the rise of the asymmetry at high $p_\perp$ and close to the central region of x_F cannot be described by the model. We believe that this rise can result only from a combination of hard scattering with the Collins effect. The former has not yet been included in our calculation.

6. Discussion and conclusions

To summarize, we calculated the single transverse spin asymmetry in high-energy pp collisions in a simple model involving the Collins effect (asymmetry arising at the level of fragmentation of a quark into hadrons). We parametrized the Collins effect by the Lund mechanism of polarization in the coloured string model.

We got good agreement with the data when we assummed that:

a) The transverse polarization of the u and d quarks in the transversely polarized proton are close to unity but of the opposite sign ($\vec{\mathcal{P}}_u = \vec{\mathcal{P}}_{\text{proton}}, \vec{\mathcal{P}}_d = -\vec{\mathcal{P}}_{\text{proton}}$) at momentum fraction x close to 1.

b) The dependence of the quark transversity (or polarization) on the momentum fraction x is close to be proportional to x^2.

The conclusion a) is model-independent provided that the asymmetry arises in the quark fragmentation (Collins effect), which is a reasonable assumption as argued in section 2.

The quark transversities we got :

$$\frac{\Delta_\perp G_u(x)}{G_u(x)} \approx -\frac{\Delta_\perp G_d(x)}{G_d(x)} \approx 1 \qquad (\text{for } x \to 1) \tag{6.1}$$

are, in fact, not unreasonably large. Consider a covariant model of the baryon consisting of a quark and a bound spectator diquark [13,17] ; then

$$G_{q\uparrow/B\uparrow}(x) = \frac{x}{16\pi^2}\int_{-\infty}^{q_m^2} dq^2 \left(\frac{g(q^2)}{q^2 - m_q^2}\right)^2 \sum_{\text{diquark polarization}} |\bar{u}(q\uparrow) V u(p\uparrow)|^2 \qquad (6.2)$$

where $g(q^2)$ is the $q - qq - B$ form factor, $V = 1$ for a scalar diquark, $V = \gamma_5\gamma\cdot\varepsilon$ for a 1^+ diquark of polarization ε^μ and

$$q_m^2 = x m_B^2 - \frac{x}{1-x} m_{qq}^2 \, . \qquad (6.3)$$

Formula (6.2) is similar to the covariant Weizsäcker–Williams formula, but for a "spin $\frac{1}{2}$ cloud"). Independently of $g(q^2)$, this model predicts the following behaviours at $x \to 1$:

- for a 1^+ spectator diquark, helicity is fully transmitted [$\Delta_L G_q(x)/G_q(x) \to 1$], transversity is fully reversed [$\Delta_\perp G_q(x)/G_q(x) \to -1$]. In particular, $\mathcal{P}_d(x) \to -1$.
- for a 0^+ diquark, $\Delta_\perp G_q(x)$ and $G_{q^+}(x)$ coincide and, for $g(q^2)$ decreasing faster than q^{-2}, they exceed $\frac{2}{3}G_q(x)$ as $x \to 1$

Thus, a dominance of the scalar spectator for the u quark and the pseudo-vector one for the d at $x \sim 1$ could lead to the large opposite transversities as in (6.1).

The conclusion b), related to the x_F dependence, is model-dependent and cannot be taken too seriously. One needs a good parametrization of the Collins effect before one can deduce the x dependence of the quark transversity. Our parametrization is an approximation which should work only at reasonably high values of both x_F and p_T. We took into account the Collins effect only for the first-rank (leading) hadrons, wherefrom $\mathcal{A} \propto z$ in (3.3). The second-rank hadrons have the asymmetry of the opposite sign as compared to the first-rank ones. More generally, the subsequent ranks are asymmetric in the opposite way to each other (as required also by local compensation of transverse momentum). This should cause a faster decrease of $\mathcal{A}$ at lower z values, where the higher-rank hadrons are more important. Unfortunatly this feature was not possible to include in our simple semi-analytical calculation, since the yields of rank-2 (and higher) hadrons do not have simple analytical forms. The contribution of vector mesons also should reduce $\mathcal{A}$ at lower z. Assuming $\bar{x} \sim \bar{z} \sim \sqrt{x_F}$, a steeper $\mathcal{A}$ (for instance $\propto z^2$) would imply a flatter $\mathcal{P}_q(x)$ (for instance $\propto x$).

In our model the high $p_\perp$ hadrons originate from the tail of the Gaussian distribution of the intrinsic and tunneling transverse momenta. Incorporating the hard scattering should not change the results very much at large $p_\perp$. There will be some smearing of $\vec{h}_\perp$, hence a reduction of the asymmetry, but not too severe because of the "trigger bias" effect: in most high $p_\perp$ events, the contributions of string decay and of hard scattering to the transverse momentum are rather large and point in approximately the same direction, as in Fig. 1 (in order to sum up to the large $\vec{p}_\perp$ of the pion). At small $p_\perp$, the trigger bias effect would work less and this could improve the agreement with the data in that region (Fig. 4b).

One main conclusion of this paper is that single spin asymmetry may be the first experimental indication for the existence of the Collins effect. A more detailed experiment would be usefull to select between this and alternative explanations. Besides its theoretical

interest, the Collins effect may be the most efficient "quark polarimeter" necessary for the measurements of the transversity distributions in the nucleons [5,18]. We hope that this effect will soon be tested directly, for instance in the azimutal correlation of two pion pairs from opposite quark jets in e^+e^- annihilation.

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Figure captions

Fig. 1 Inclusive pion production. Two events (a) and (b), symmetric with respect to the yz plane, are represented. Without polarization, they would have the same probability. In the polarized case, the Collins effect favours the case (a).

Fig. 2 Production of the leading pion in a string drawn by a transversely spinning quark.

Fig. 3 Single spin asymmetry measured by E704 collaboration. The curves are our model results calculated with quark transverse polarizations at $x = 1$ as in SU(6) wave function of the proton ($\mathcal{P}_u = 2/3$ and $\mathcal{P}_d = -1/3$). The data are from Ref. [7].

Fig. 4 The asymmetry calculated under an assumption that the quark polarizations at $x = 1$ are: $\mathcal{P}_u = +1$ and $\mathcal{P}_d = -1$. The data are as in Fig. 3.

Fig. 5 Comparison of two various quark distributions. The full lines and the data are as in Fig. 4.

Fig. 6 The asymmetry of π^0's. Here there is no difference between the predictions of SU(6) and the maximal polarizations. The quark distributions are as in Figs 3 and 4. Data come from Ref. [6].

Fig. 7 $p_\perp$ dependence of the π^0 asymmetry in two intervals of the Feynman variable x_F. Data are from Ref. [8].

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